Railway System Optimization Seen from an Energy Management Perspective

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JR East consumed a huge amount of energy in train operation and at buildings such as stations, amounting to 6.1 billion kWh of electricity and 91,000 kl of oil and gas (crude oil equivalent) annually. Energy consumption is structured by there being services that must be provided, those demanding rolling stock systems and facility equipment capacity, and those demanding energy consumption. System innovation to reduce the load on the environment must thus start with knowing the demand (load) for energy consumption and reducing that load. This article will introduce the approach from an energy management perspective to technical innovation that optimizes railway systems and reduces environmental load.

Introduction

Railway business provides transport services by operating trains and running stations. Such operation plus maintenance of rolling stock and equipment that supports operation can be called the aggregate of railway business. Energy consumed annually by JR East in railway business is a tremendous 6.1 billion kWh of electricity and the crude oil equivalent of 91,000 kl in oil and other fuels when combining consumption by train operation and by buildings such as stations (Fig. 1).

The JR East group has a mission to achieve reductions in such consumption, no matter how small they may be, and to reduce the environmental load of railways. We are working steadily towards that goal as seen by results such as having introduced energy-conserving rolling stock such as the series E231 and E233, adopted high-efficiency equipment such as LED lighting, and utilized renewable energy such as solar power generation.

Energy conservation has, as shown in Fig. 2, a structure whereby first there are services that must be provided, then rolling stock systems and facility equipment capacity are required to provide the services, and finally that capacity demands energy consumption. Energy consumption alone cannot be reduced without reducing demand (load). Energy conservation can thus be achieved by the approach of measuring and assessing to know the load, making changes to reduce load, and building optimal systems that meet the load. Therefore, it is important to have a technical philosophy of building management to solve from “inside” issues found in measurement and assessment, instead of just introducing high-efficiency items from “outside”, and innovating systems from that perspective.

This discussion introduces technical innovations to reduce the environmental load of railways, separating train operation and building operating systems.
Energy for train operation is consumed by the rolling stock drive system (main circuit system made up of drive motor and controller for EMUs) and auxiliary system (auxiliary devices such as air conditioners and lighting). Therefore, energy-conserving train operation is the first topic for achieving high-efficiency rolling stock systems.

Meanwhile, energy efficiency for devices such as drive motors and air conditioning changes by the moment depending on operating status, so running devices with good efficiency in actual train operation is the next topic: economic operation of trains. It can be compared to making a talented athlete (high-efficiency rolling stock system) achieve excellent results (energy conservation) by performing in top condition (economic operation of train).

Lastly, we achieve an overall optimal energy network, aiming for effective use of regenerative energy. Specifically, various methods can be assumed such as application of electrical storage technologies, energy conservation as a group of trains expertly combining powered running, coasting, and regeneration, and exchange (power interchange) between substation systems that supply power to trains and power distribution systems that supply power to stations and the like.

By building up in order of solutions to issues for achieving energy conservation, a three-level structure (Fig. 3) for high-efficiency train operation comes together.

Such a railway system optimized from energy management deserves to be called a railway version smart grid. A possible approach to achieving that is to start with optimizing the first and second level systems that make up load and then to optimize the third level system.

![Fig. 3 Three-level Structure of High-efficiency Train Operation](image)

We have been proceeding since fiscal 2011 with R&D on making main circuit systems more efficient (Fig. 4). To start with, we have been continuing with studies that put the directionality of system innovation into perspective while looking back on the history of main circuit design. In direct current motor driving, main motor design guidelines have been systemized as theory on performance, capacity and rating, but systemization for induction motors is not yet sufficient. Starting in fiscal 2012, we have been going forward with systemizing main motor design guidelines and with test production and running tests for hardware using new main current elements.

### System plan for high efficiency
1. Reduce iron/copper loss
   - Lower motor flux/current density (Decrease motor size within permissible range)
   - Core FL material loss resistance
2. Reduce motor secondary copper loss
   - Reduce slip frequency (Make control highly accurate)
3. Reduce loss by innovating main circuit elements
   - (GTO switched to IGBT)
   - Snubberless
   - Make gate driving require less power
4. Reduce loss by innovating of main circuit elements
   - (Si switched to SiC)
   - Reduce main circuit element loss
   - Plan system optimization (Make carrier frequency high frequency, etc.)

Next is economic operation. For drive motors, we created “efficiency maps” like in Fig. 5 that show how energy efficiency changes depending on running speed and tractive force. Based on that, we propose notching curves where the most efficient notching is selected for the train to follow (the most beneficial route) and train performance curves where powered running, coasting, and regeneration are combined in the optimum manner.

Finally, there is technical innovation to effectively use regenerative energy. The actual situation regarding regenerative energy must be clarified in this, but regeneration performance is simply shown as ability of rolling stock. How much that ability can be exhibited is not known without measuring. We thus have been developing a means to quantify operating energy.

Up to 2011, we placed measuring devices on both substations and rolling stock on the Sagami Line, using those to establish a method of quantifying consumed energy. Staring in 2012, we have been attempting to measure and assess energy under the complex conditions of lines such as the Yamanote Line and Tohoku Shinkansen. In conjunction with that, we started research in fiscal 2012 on measuring and analyzing charging and discharging behavior when storage batteries are set up in substations.

![Fig. 4 Making Main Circuit System Highly Efficient](image)
Next, is an introduction to the approach to innovation in building systems. The Environmental Engineering Research Laboratory has been continuously conducting R&D for constructing the optimum systems for building spaces such as underground stations, general rolling stock centers, and signal communication equipment houses upon reducing equipment service load. Those spaces are unique to railways, so we believe that it is the obligation of railway technologies to propose solutions for system innovation.

Of railway equipment, that for air conditioning in underground spaces such as the Sobu underground station features large-scale systems and is characterized by having large energy consumption. Air conditioning load for platform levels especially tends to be large due to conditions such as the large opening for tracks (tunnels) and heat radiating from cars. Energy-conserving improvement upon optimum assessment of load is something that has long been sought after.

Meanwhile, spaces such as general rolling stock centers where multiple functions are amassed use large amounts of electrical power and steam. We are thus supporting efforts to “visualize” such electrical power and steam use and eliminate waste. We are also looking to envision the ideal form that minimizes environmental load (eco factories). To start with, we identify work functions such as body and component repair spaces, planning functions such as conference rooms, and living functions such as baths and cafeterias, coming up with ways to reconsolidate those and lay each of those out in a compact manner. Next, we come up with architectural and equipment plans to realize those and come up with an overall optimum energy network that supplies electricity and steam to those functions in the end. The three-level structure of eco factories where those are built up in order is shown in Fig. 6.

Last is an introduction of the air conditioning equipment of signal communication equipment houses. This could be called an untouchable area that supports train protection, but coordination between the operating users and people in charge of equipment could lead to elimination of waste by cooling the equipment in a more effective manner. We propose system improvement where the specific field is selected, that field is measured and assessed, and issues found in that process are solved.

Development started in 2009 for reassessing load of underground air conditioning for the Sobu Line underground area at Tokyo Station using the latest data and computer simulations. The assessment showed that actual load is far less than design conditions. It also showed that the platform level air conditioning method is not functioning appropriately, making the load unnecessarily large. We thus proposed a revision (Fig. 7) to that.

By improving the air conditioning system in line with the discoveries, we found that we could probably reduce the heat source of 2,577 USRT to 1,010 USRT, sliming down the system to approx. 40% that of the current system.

In conjunction with load assessment, we are looking back at the history of underground station design from the late 1960s to today. Fig. 8 shows a comparison of underground station platform level air conditioning methods starting from the oldest. This shows that the aforementioned proposal for improvement of the Sobu underground area platform level resembles that of the newest method employed at the Sendai Station Senseki Line underground area. If we make energy conservation improvements to underground station platform level air conditioning designed before the Senseki Line underground area, a significant effect can probably be expected. After all, equipment capacity was excessively designed overall, so streamlining of capacity can most likely be anticipated through measurement and reassessment.

From looking back at the history of design in this manner, we were able to gain an outlook for energy conservation at underground stations in general, not just the Sobu underground station. Moreover, in assessment of other underground stations from fiscal 2011, the issue intrinsic to intermediate stations

![Performance curve (example)](example_image)

![Efficiency](low → High)

![Overall optimal energy network](Electricity/steam)

![Architectural plan](Equipment plan)

![Compact layout of functions](Fig. 5 Drive Motor Efficiency Map)

![Fig. 6 Three-level Structure of Eco Factory](example_diagram)
(Shimbashi, Bakurocho, etc.) where humidity is too high and cooling ability was not sufficient to achieve the expected air conditioning function was found in addition to issues similar to those of the Sobu underground station. In light of this situation, development was started in fiscal 2012 for systemizing improvement guidelines to support energy conservation for underground air conditioning.

Meanwhile, systems can be built to achieve energy management for areas such as stations, station buildings, and stationfront hotels by utilizing the station’s excess capacity in surrounding area. This goes beyond simply applying load assessment to station energy conservation. Optimum energy management for load-concentrating areas intrinsic to railways such as general rolling stock centers, stations, and facilities surrounding stations can be called a “railway microgrid.”

### Conclusion

This article introduces technical innovation with a focus on energy conservation. While not covered here, another pillar of reducing environmental load is utilization of renewable energy. With an aim of application to the field of railways, we are developing grid connection control that more effectively utilizes solar energy and methods of utilizing geothermal and aerothermal energy using heat pumps.

The Environmental Engineering Research Laboratory, which started in April 2009, began R&D with development of systems for EMUs that run on storage batteries and assessment of air conditioning loads for the Sobu Line underground area at Tokyo Station. Some positive results have been achieved, so we will take on various development projects in system innovation from a perspective of energy management.

We are positive that the approach of assessing and optimizing systems from an energy management perspective will innovate railway technologies. And that innovation should bring to society results such as energy conservation, power saving, and CO₂ reduction.